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VII.

A METHOD OF OBTAINING AND OF MEASURING
VERY HIGH PRESSURES.

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Presented June 11, 1890.

1. *Historical.*—Andrews's screw compressor has this advantage, that the acting stress is brought to bear within the compass of the barrel. In other arrangements, such, for instance, in which a cylindrical plunger is forced into the barrel, stress must be exerted against the bedplate, or applied in a way tending to flexure the plunger. The screw compressor may therefore well be taken as the model of an apparatus of greater strength and efficiency than was necessary in Andrews's work. Indeed, Andrews himself seems to have been of this opinion,* and toward the close of his life devised an apparatus of which screw plungers are an essential part. Hannay and Hogarth,† however, were the first to carry the practical improvement of the screw into execution. They reached pressures but slightly short of 900 atmospheres, stating that their reasons for stopping work at this datum were quite apart from the efficiency of their apparatus. With the screw compressor ‡ described below, I obtain above 2,000 atmospheres with facility. §§ 17, 23. It is so constructed that a considerable volume of liquid is operated on, admitting of a compression of five cubic inches of volume decrement. Finally, special provision has been made for the insulation of parts, thus enabling the observer to apply the essential electric methods § in studying his test samples.

Particular notice should here be given of the remarkable modification of Desgoffes's differential manometer, by which Amagat || succeeded

* See Professor Everett's account in *Nature*, Vol. XXXIX. p. 556, 1889.

† Hannay and Hogarth, *Chem. News*, Vol. XLI. p. 103, 1880.

‡ It was made for me by the American Tool Co., No. 84 Kingston Street, Boston, Benjamin J. Radford, Superintendent.

§ I here have special reference to Tait's ingenious device. See *Proc. Roy. Soc. Ed.*, Vol. XIII. p. 2, 1884–85. *Beiblätter*, X. p. 149, 1886.

|| Amagat, *C. R.*, Vol. CIII. p. 429, 1886.

in reaching and of measuring over 3,000 atmospheres. To my knowledge Amagat has as yet given only a meagre account of his machine. Fortunately, however, Professor Tait* recently described the "manomètre à pistons libres" at length, in connection with his own researches. Special comparison of the respective advantages of Amagat's apparatus and the machine of the following papers seems therefore uncalled for.

The Bourdon gauge has been recently discussed by Mr. Worthington† and by Professor Greenhill.‡ The high pressure Bourdon gauge used in my work was of the kind described by the latter.

SCREW COMPRESSOR.

2. *Disposition.*—The apparatus (Fig. 1) consists essentially of a strong wrought iron barrel, *ABC*, the head of which, *AA*, is suitably threaded, so that a steel screw, *SSTT*, can be forced into it. The piezometer tube is attached at the end, *CC*, of the barrel. Barrel and tubes are quite filled with oil.

3. *Special Devices for preventing Leakage.*—The first of these is the tinned screw. This is an ordinary well cut machine screw of iron or steel, covered with a uniform thin adhesive layer of ordinary solder by dipping it in a vessel of the fused metal. Soldering salts are used in the ordinary way. When forced into their sockets, these screws secure complete freedom from leakage, even at 2,000 atmospheres and more. Gauges and other appurtenances may thus be attached to the barrel, and removed from it with facility.

The other device is the gasket of marine glue,§ or similar very viscous liquid. A stuffing box is easily made, by which this substance is kept pressed against the threads of the screw, or against the smooth surface of a cylindrical plunger. Now whereas the cement admits of being shaped by pressure to fill up any cavity, it is yet far too viscous to flow through capillary interstices, except after the lapse of an enormous time (months). Thus I found the absolute viscosity (*g*/cm.sec.) to be 200×10^6 , that is, about 20 billion times the vis-

* Tait, Challenger Reports, 1873-76, Physics and Chemistry, Vol. II. See Nature, Vol. XLI. p. 361, 1890.

† Worthington, Nature, Vol. XLI. p. 296, 1890.

‡ Greenhill, Nature, Vol. XLI. p. 517, 1890.

§ Supplied by M. Ducretet of Paris, the Société Gènevoise, and doubtless by many others. It is a specially prepared mixture of rubber and shellac. To thicken it, more shellac may be added. Perhaps pitch, or even molasses candy, would be similarly serviceable.

cosity of water. It would therefore require 1,000 atmospheres to force this sample of marine glue through a capillary tube .01 cm. in diameter and 1 cm. long, at the small rate of .05 cm. per hour, supposing (an unfavorable supposition) that its viscosity does not increase under pressure. Pressure moreover tends to close capillary interstices between nut and screw, thus making the apparatus even more efficient at high pressures than at low pressures. At high pressures, finally, a single turn of the screw has a much larger pressure equivalent, for the compressibility of the oil has materially decreased.

4. *Steel Screw*.—To rotate the screw *SSTT* (Figs. 1, 2, 3), it is provided with a lever and ratchet, *LDR*. The ratchet wheel is shown at *RR* (Figs. 1, 3), and is square-cut to correspond with the right and left click, *D*. A pin, *E*, sliding in a socket of the lever, *L*, and actuated by a spring (Fig. 1), enables the observer to adjust the ratchet either for forward or retrograde motion of the screw *ST*. The figure gives a full account of the manner in which the parts of lever and ratchet are put together, and I need only add that the (steel) ratchet wheel *RR* is forged to the shaft *T* of the screw.

The screw *SS* is one inch in diameter with twelve threads to the inch. The shaft *TT* is held in position by a journal, *HHH*, fixed between slides (see Fig. 2), and bolted securely down to the bedplate *FG*.

5. *Barrel Head*.—The planed front end of the cast iron bedplate *FG*, the part *FF* of which is hollowed out to catch drippings, carries the barrel *BBB*. It is seen in cross-section in Figure 4, and its flat side is firmly secured between the guides of the bedplate, by two bolts (Figs. 1 and 4).

KK is the stuffing screw, being essentially a hollow steel nut of the form shown, and provided with a large flange for screwing it forcibly in place. Both the inner and the outer cylindrical surface of *KK* are threaded with twelve turns to the inch. Moreover the inner thread, *bbbb*, of *KK* is a continuation of the thread *aaaa* in the walls of the barrel. Inasmuch as the thread *cccc* also has twelve turns to the inch, it is clear that the nut *KK* can be forced in or out, no matter what the position of the screw *SS* may be. In practice *cccc* is cut first, and the nut screwed in place. After this the whole thread *bbaaaabb* is cut at one time. The gasket of marine glue (§ 3) is shown at *mm*. It is compressed by *KK*. At high pressures, the friction is sufficient to hold the nut *KK* in place without the need of a lock-nut.

It is seen that after the screw *ST* enters the barrel *BB*, the chief strain is borne by the thread *aaaa*.

6. There is an objection to this form of stuffing box, inasmuch as at very high pressures the threads *aaaa* and *bbbb* tend to act as lock-nuts on each other. To obviate this annoyance I devised the method shown in Figures 9 and 10. Here the thread *aa* is movable, being on the inside of a ring, *rr*, of steel, which fits snugly in a socket of the barrel. The ring *rr*, though capable of moving back and forth, cannot rotate, being prevented by the projection *s*, corresponding to a slot in the barrel. In this way the material in the stuffing box is not forced into the barrel on actuating *KK*. Note that the thread within *KK* is carried quite to the end, and that the inner face of *KK* is bevelled very obliquely, thus allowing the gasket to encircle a greater number of threads of the screw *SS*. The strain is now borne by the thread *bb*. Experiment has shown this to be no disadvantage.

7. *Barrel. Body.*—This is perforated by four or more holes (Fig. 1), about $\frac{3}{8}$ inch in diameter, and threaded to admit the tinned machine screws. Two of these, *MM*, are vertical, the other two, *N*, *O* (Fig. 4), horizontal. They are of use in filling the barrel with oil, for attaching gauges and other appurtenances.

8. *Barrel. End with Piezometer Tube.**—These steel tubes, *UUU*, are inserted in such a way as to insulate them electrically from the barrel end *CC*. A screw is cut on the end of *UUU*, fitting into a cast iron flange, *WW*, between two cylindrical jackets, *XX* and *YY*, of hard rubber or ivory. These parts *Y*, *W*, *X*, are screwed to the end of the tube *U*, and the cylinders *Y* and *X* are turned large enough to fit the hole of the barrel and the internal aperture of the steel nut *ZZ* snugly. All space within the head *CC* is filled with marine glue, *dd*. This is easily accomplished by melting the cement into the crevices between *Y* and *W*, *W* and *X*, before putting the piezometer in place. A thick gasket, *dd*, is also inserted. After this the remaining annular space around *W*, through which leakage might occur, is filled by forcing in the nut *ZZ* gradually, and at a temperature not too low.† To

* Weldless cold drawn steel tubing of any dimension may be obtained from John S. Leng, New York, or of Philip S. Justice, Philadelphia, U. S. A. Both gentlemen are agents of English houses whose address is not known to me.

† The figure is somewhat diagrammatic here to exhibit the parts. In practice I use hard rubber cylinders *XX* and *YY*, and two hard rubber annular disks between *YY* and *WW*, and *WW* and *XX*, respectively. When ready for insertion, the cylinders are screwed against *WW*, so that there are mere films of marine glue left between contiguous planes. Finally, the nut *ZZ* is brought in contact with the flange of *YY* (disk) by pressure. It is in view of the fact that *YY* is pressed radially inward toward the axis of *UU*, as well as outward by pressure, that the arrangement holds so well. Repacking is only rarely neces-

obviate the possible electric contact between *W* and *ZZ*, the hard rubber jacket *Y* is suitably flanged. *XX* is also to be flanged (not shown).

9. *Piezometer Tube and Vapor Bath*.—The outer end of *UUU* is closed by the tinned screw *V*. The substance to be examined is here introduced, usually in glass tubes; but the special devices to be adopted for each special experiment are beyond the scope of the present paper. As a rule, the glass sample tubes are adjusted within the compass of the copper vapor bath *ffff* (Fig. 5), which surrounds the steel tube *UU* eccentrically. The vapor bath is merely a long cylinder of brazed sheet copper, containing the liquid *yy*, to be boiled by heating it with a large burner. Vapors escaping at *g* are condensed (condenser not shown) and run back, thus making the ebullition continuous. A number of baths of this kind are at hand, each containing a substance of suitable boiling point. In order to pass from one temperature to another, it is merely necessary to slip off one vapor bath, *ff*, and slide on another. The copper vessels *ff* are of course surrounded with thick asbestos jackets, and proper provision is made to close up the ends of the end tubes *hh*. As far as temperatures not exceeding 200°, perforated rubber corks are satisfactory. For higher temperatures, *hh* are stuffing boxes containing asbestos wicking tightly appressed. It is preferable to lead off the vapor by a long lateral oblique gas-pipe (not shown) and to use the tubulure *g* for the insertion of the thermocouple* for measuring temperature. A tube or jacket through which cold water circulates must surround the piezometer *UU*, between *ff* and the barrel, and between *ff* and the end screw *V*, otherwise the heat conducted along the tube *UU* will eventually melt both the marine glue and the solder joints. It is for the same reason (heat conduction) that annular vapor baths of the kind described in the Bulletin of the U. S. Geological Survey, No. 54, Chapter II., are not admissible. Heat is conducted along the metallic tube more rapidly than it is supplied, and constancy of temperature cannot be guaranteed nor easily measured. It is essential that the vapor be directly in contact with the piezometer tube. Indeed, when very fine temperature work below 200° is necessary, I use the drum *ff* simply for

sary. I may add, that as an insulator marine glue is not absolutely perfect, the resistance here being a few hundred thousand ohms. For very fine electrical work some other material may be used.

* Cf. Barus, Bull. U. S. G. S., No. 54, 1889, p. 22; Phil. Mag., Vol. XXIX. p. 141, 1890. A special torsion galvanometer, used for measuring the thermoelectric powers, is to be described elsewhere.

the reception of vapor, leading it in at one end and suitably withdrawing it at the other. Low temperatures are obtained by a jacket of circulating water.

10. *Method of Filling.*—When the screw is in good adjustment, fresh supplies of oil are not frequently necessary. The method of filling is indicated in Figure 4. The steel rod *OO*, threaded and tinned at one end, and provided with a strong cross handle at the other, is enveloped by a brass tube, *P*, surmounted by a funnel-shaped inlet, *Q*. Both *Q* and *P* are kept full of oil, and there is an ordinary stuffing box at *pp*. A spring clamp (not shown), keeps the end of *P* pressed against the side of the barrel *BB*, a suitable leather washer being interposed. To fill the barrel, take off the pressure and screw out *OO*, without removing it from *P*. The oil will then follow the retreating screw *ST*. One of the screws *M* may finally be removed, until the oil exudes; for it is clearly advisable to expel air, which must be considerably reduced in volume before it will sustain high pressure.

Ordinary sperm oil or machine oil of a thickish quality is available for filling the barrel. It has an advantage over water in protecting the screw against rust, and perhaps in keeping the moving parts oiled. Mercury is not available, since it would dissolve the tin coatings on the bolts.

11. *Case for Protection.*—Working as far as 2,000 atmospheres explosions are not infrequent. They occur with slight detonation, scattering thin mists of oil; but there has been nothing of a serious nature. It is well to surround the barrel with a case of two-inch plank, and to provide a barricade beyond the end of the piezometer tube. A suitable tin pan placed underneath the bedplate of the screw is of use in catching oil. After filtering, it may be used over again.

The whole apparatus usually works better after some use than immediately after packing. Indeed, it often happens that a tendency to leak shown at 500 atmospheres quite disappears at 2,000 atmospheres, for the packing is compressed and solidified, and the moving parts oiled.

12. *Vertical Piezometer.*—An adjustment similar to *CC UU*, but smaller in dimensions and ending below in a finely perforated screw, may be attached at *M*. The piezometer is thus fixed in vertical position, and is easily adjusted or withdrawn, while the end of the barrel is available for other purposes. § 23.

PRESSURE MEASUREMENT.

13. *Tait Gauge.* Adjustment.* — The gauge is inserted at N (Fig. 4), and is shown at qq , tt , ss . The essential part is the steel tube qq , closed at one end by a close-fitting tinned bolt, r , soldered in place, and connecting at the other end with the cup-shaped junction N . It is not advisable to cut a deep thread in the tube qq . It may, however, be fastened into N by a fine shallow thread and solder; and the deep thread cut in the thick-walled tube of N , which is then tinned and screwed into the barrel.

To measure the expansion of qq under pressure, it is surrounded by a close-fitting glass tube ttt , one end of which is joined to the steel tube qq by a layer of marine glue. To do this the tubes qq and tt are clamped in position vertically, with the open end uppermost. A sheet of thin copper foil is wrapped tightly around the end of tt , and fastened with wire so as to project somewhat above it, forming a small annular trough. Marine glue is put into this, and the burner applied cautiously from without. The fused marine glue slowly flows down into the space between the glass tube and steel tube, and the heat is withdrawn when the layer is an inch or two in length. When cold, fusible metal is poured into the copper trough in the space left by the glue. The joint thus formed is not only tight, but reliably rigid.† Space must be left for the elongation of the steel tube.

The other end of the glass tube tt communicates with the capillary tube ss by which the expansions are measured. In Figure 4 this is shown vertically; but it is expedient to bend it horizontally, parallel and close to the jacket uu , to which it is rigidly fastened directly over a suitable millimeter scale. In this way the capillary, though 70 cm. or 80 cm. in length, is protected against injury. I may state, in passing, that pressure on the outside of the tube tt appreciably displaces the meniscus in ss , an error which must be guarded against. It is well, however, to bring slight and constant air pressure to bear on the meniscus, by attaching a U -tube containing mercury to the end of the capillary.

* The form of steel high pressure gauge based on Hooke's law recommended but not constructed by Professor Tait (*loc. cit.*), is somewhat different from the above. I think my form has the practical advantage of greater simplicity, being essentially a single-walled tube. The method of computation is due to Professor Tait.

† It was my purpose to make the tube tt of brass, so that the heat of compression would be more quickly dissipated. But I failed to obtain tubing of the proper bore and strength.

The shell-like space between steel tube qq and glass tube tt is filled with a liquid of small coefficient of expansion. I first tried mercury, but found it almost impossible to fill tt in such a way as entirely to exclude air. It is clear, in view of the friction of the mercury thread in ss , that any trace of air in tt will vitiate the experiment. The thermal expansion of colored alcohol is too great. I therefore used water containing a little alcoholic solution of fuchsine. This is introduced through the capillary, by evacuating the tube tt . It is necessary to repeat the operation a number of times, and to boil out traces of air. I obtained the requisite constancy of temperature, by surrounding tt with a jacket, uu , of circulating cold water coming directly from the hydrant. To put the liquid in ss at a given fiducial mark, a special adjustment for moving the meniscus suggests itself; but this is an exceedingly difficult device to apply, seeing that there must be a minimum of water in tt , and that absolutely tight joints are essential. Hence I raise or lower the meniscus, and color it when faded, by inserting filamentary glass suction tubes into the canal ss . There is then little difficulty either in adding more liquid to the thread, or in withdrawing liquid from it. Cf. § 14. The steel tube qq should be protected against rust, by nickel-plating it. I found, moreover, that water free from air and containing a little alcohol scarcely attacks steel; for bright surfaces remain bright after many months.

By using a long steel tube the effective length can be more accurately stated, for the length error at the joint tq is proportionately decreased. Again, since the expansion corresponding to a given pressure increases in absolute magnitude with the length of qq , a wider capillary, ss , suffices for measurement when qq is long. This facilitates the adjustment for fiducial zero already given.

14. *Tait Gauge. Graduation.*—To accomplish this I compared the gauge with a large Bourdon gauge* reading from 0 to 1,000 atmospheres. § 1. The tube of the latter communicated with the barrel, through one of the screws M . This comparison is a check on both instruments, and the statistics are therefore given below in detail. It affords no means of testing the value of the standard atmosphere employed; but since both gauges are based on Hooke's law, and provided with suitable scales of equal parts, the relations are well indicated. In the table, $2A_0$, $2A_1$, and L denote the internal and the external diameters and the length, respectively, of the steel gauge tube qq , Figure 4; 2ρ is the bore of the capillary tube ss .

* Furnished by the Société Gènevoise.

TABLE I. — COMPARISON OF TAIT GAUGE, No. 0, AND BOURDON GAUGE.

$$A_0 = .27 \text{ cm.}; A_1 = .50 \text{ cm.}; L = 100 \text{ cm.}; \rho = .034 \text{ cm.}$$

TIME = — GAUGE, Bourdon.	15 m. Tait.	30 m. Tait.	45 m. Tait.	75 m. Tait.	90 m. Tait.
atm.	cm.	cm.	cm.	cm.	cm.
0	1.90	2.10	2.00	2.18	2.16
100	3.58	3.70	3.60	3.85	
200	5.20	5.50	5.35	5.55	
300	7.05	7.25	7.20	7.45	7.30
400	8.70	9.00	8.90	9.10	
500	10.50	10.72	10.70	10.85	
600	*12.50	12.50	12.45	12.55	12.70
700	14.10	14.10	14.10	14.20	
800	15.65	15.70	15.70	15.85	
900	17.22	17.20	17.30	17.45	
1000	18.80	19.00	19.00	19.10	19.20
900	16.62	16.70	16.80	16.80	
800	14.65	14.70	14.63	14.70	
700	12.80	12.80	12.75	12.92	
600	10.95	11.00	11.00	11.12	11.00
500	9.30	9.28	9.23	9.35	
400	7.55	7.55	7.50	7.60	
300	5.95	6.00	6.10	6.15	5.85
200	4.50	4.55	4.60	4.60	
100	3.04	3.12	3.15	3.20	
0	1.74	1.90	1.90	2.00	1.60
Rate in centimeters per atmosphere	.0169	.0171	.0172	.0172	

15. The table contains five series of observations made at the times (minutes) stated. In the first four series, I went up to the maximum (1,000 atm.) and down again gradually, but not slowly. In the last, I operated as fast as the experiment would permit. To determine the degree of accuracy, the rates at the bottom of the table may be consulted. These show that a mean displacement of .0171 cm. of the meniscus takes place in the pressure increasing series, for each atmosphere. Considering data on the same horizontal row, it appears that the differences of reading of the new gauge corresponding to a given reading of the Bourdon gauge are greatest in the region of low pressures. At zero the maximum difference observed is .40 cm., equivalent to an error of 24 atm. Again, comparing the two zero readings of the last column, the difference of reading is .56 cm., corresponding to 33 atm. This, therefore, is a maximum index of the inaccuracy of the new gauge, due to the thermal effects of compres-

* Break in the measurements.

sion, and unreasonably hasty work. To diminish this error further, it is necessary to decrease the bore of the glass tube *tt*, Figure 4, thus making the thermometer feature of the gauge of smaller moment. § 18. In the above apparatus this tube was 1.15 cm. in internal diameter, corresponding, therefore, to a liquid interstratum .07 cm. thick. Clearly, this admits of further reduction. It is also feasible to decrease the strength of the steel tube, making the apparatus more delicate.

16. A second point of view is obtained by comparing the data of the pressure "on" and the pressure "off" phases of the above experiments. For convenience, I have constructed the results of Table I. in the chart, Figure 6. The degree of accordance in the "on" phase is satisfactory, since the errors are not above 10 atm., and the loci, apart from slight circumflexure attributable to the Bourdon mechanism, are straight lines. In the "off" series, this good uniformity is lost, and the data lie on consecutive broken lines. The "off" data do not return in the lines of the "on" data. Indeed, the two curves, "on" and "off," enclose a band the maximum width of which is 1.5 cm., corresponding to 90 atm. The interpretation of this curious and persistent phenomenon is therefore of importance.

17. With this end in view, I again compared the gauges after several months' use. The data are contained in Table II. At least five minutes were allowed per observation. Two complete series are given.

The second part of the table gives some data on the constancy of the zero after very high pressure. The slight shifting of the zero observed (equivalent respectively to 10 and to 5 atmospheres) is due to a mechanical imperfection which I subsequently remedied. Hence the gauge is vouched for within 2,000 atmospheres.

It is seen at once that the mean data of Tables I. and II. are identical. Hence, to account for the apparent hysteresis observed, it is necessary to construct other Tait gauges. I did this with much care.

18. *New Tait Gauges.*—The new gauges are numbered 1 and 4. No. 1 is nearly of the same length as No. 0; No. 4 is considerably shorter. The glass tubes (*tt*, Fig. 4) are as close fitting as practicable, and the capillary of No. 1 is of small bore, to insure special accuracy in reading. Of the many series of observations made, two for No. 1 are given in Table III. Table IV. contains a comparison of Nos. 1 and 4. Five minutes were allowed per observation. The capillary tubes were carefully calibrated. In the second part of

TABLE II.—COMPARISON OF THE BOURDON GAUGE AND THE TAIT GAUGE, No. 0, FOUR MONTHS LATER.

Large Bourdon.	First Series.		Second Series.		Factor.	Mean Factor.	High Pressure Tests.	
	Pressure "on."	Pressure "off."	Pressure "on."	Pressure "off."			Pressure.	Reading.
atm.	cm.	cm.	cm.	cm.	cm./atm.	cm./atm.	atm.	cm.
100	6.40	6.30	6.35	6.20	.01715	.01722	0	4.90
200	8.10	7.95	8.03	7.88	.01725		2110	40.93
300	9.87	9.70	9.80	9.60	.01720		0	5.10
400	11.57	11.39	11.50	11.32	.01728		2160	41.95
500	13.29	13.23	13.20	13.12			0	5.20

TABLE III.—COMPARISON OF LARGE BOURDON GAUGE WITH THE TAIT GAUGE No. 1.

$\rho = .0220 \text{ cm.}; L = 100 \text{ cm.}; A_1 = 1 \text{ cm.}; A_0 = .27 \text{ cm.}$

Large Bourdon.	Pressure "on." No. 1.	Pressure "off." No. 1.	Large Bourdon.	Pressure "on." No. 1.	Pressure "off." No. 1.
atm.	cm.	cm.	atm.	cm.	cm.
0	17.81	17.96	0	5.96	6.21
100	21.30	21.00	100	9.42	9.14
200	25.03	24.31	200	13.17	12.36
300	28.85	27.75	300	17.00	15.74
400	32.63	31.32	400	20.74	19.13
500	36.50	35.12	500	24.60	22.84
600	40.35	39.11	600	28.45	26.75
700	44.05	43.10	700	32.15	30.76
800	47.55	47.12	800	35.78	34.75
900	51.25	51.27	900	39.57	39.00
			1000	43.36	43.40

Table IV. both gauges are standardized by comparison with a small sensitive Bourdon gauge, identical with the large Bourdon gauge. F_1 and F_4 are the factors of the Tait gauges Nos. 1 and 4, thus found.

TABLE IV.—COMPARISON OF TAIT GAUGES NOS. 1 AND 4.

No. 1, $L = 100$ cm.; $A_0 = .27$ cm.; $A_1 = 1$ cm.No. 4, $L = 58$ cm.; $A_0 = .27$ cm.; $A_1 = 1$ cm.

No. 1.	No. 4.	Small Bourdon.	No. 1.	No. 4.	F_1 .	F_4 .
cm.	cm.	atm.	cm.	cm.	cm./atm.	cm./atm.
—0.40	12.40	0	—1.30	12.02	3.65	1.63
+8.38	16.45	100	+2.28	13.63	3.69	1.67
18.23	20.85	200	6.00	15.29	3.60	1.67
28.43	25.40	300	9.66	16.97	3.73	1.61
38.36	29.80	300	9.65	16.96	3.69	1.66
50.04	34.91	200	5.90	15.26		
59.93	39.41	100	+2.20	13.62		
63.75	41.25	0	—1.30	12.04		
55.03	37.33					
42.89	32.06					
31.90	27.19					
20.09	21.86					
+9.02	16.78					
—0.55	12.30					

In series of the kind given in Table III., the agreement of observations occupying similar positions in similar series is always very close, the mean difference being only 1.2 atmospheres. Nevertheless, the data of Table III. still show decided hysteresis. (See Fig. 6.) The maximum horizontal distance apart of the "on" and "off" series is about 40 atm. Comparing Tables I., II., and III., therefore, the persistence of the apparent lag phenomenon may therefore be considered proved. I further substantiated this inference by grading the cycles.

19. *Errors involved.*—It is expedient to examine the chief errors involved. The discrepancy in question cannot be due to an imperfect Bourdon mechanism; for in adjusting the pressure at any given value just before observing, the actual pressures must as frequently be incremented as decremented, both in the "on" and the "off" series. Again, the liquid adhering to the walls of the capillary of the Tait

gauges would show its largest discrepancy at zero atmospheres following a high pressure. Change of temperature of the water jacket (*uu*, Fig. 4), or change of the water pressure, could not give rise to persistent cyclic curves, but would show itself in a displaced fiducial zero.

I think the clue for the interpretation of the apparent hysteresis is the observation that data of the "on" series lie on straight lines, whereas the locus of the data belonging to the "off" series is curvilinear. The cycles have the form of an archer's bow. Hence, bearing in mind that the liquid in *tt* is being heated by compression of the oil in the gauge during the "on" series, and that, even though gradually parting with its heat increment, it is nevertheless *continually* hotter than the surrounding medium; bearing in mind, moreover, that in the "off" series the water in *tt* is cooled by expansion of the oil in the steel gauge, but that *the water is hotter than the surrounding medium only during the high pressure stages, and colder than the surrounding medium during the low pressure stages* (heat having been continually dissipated), — an explanation of the bow-shaped cycles is suggested. Even my last and best Tait gauges, considered as thermometers, are unfortunately very sensitive instruments, showing displacements of 1 or 2 centimeters per degree Centigrade. In Table IV. the cycles are reduced in width, the distance apart being equivalent to only 17 atmospheres; but the error in question here occurs differentially.

A bow-shaped cycle may also be conceived to result as a viscous phenomenon, if a strain (set) were gradually impressed on the gauges during the "on" series, which strain would then assert itself during the "off" series. Without stopping to examine this consideration, I believe the former explanation more probable.

It follows from the present inquiry as a whole, that, to obtain thoroughly trustworthy data, pressure observations should be recorded during the pressure increasing phase of the work. In most experiments this condition is easily fulfilled, since the pressure datum sought is usually reached from zero. Finally, the steel gauge tube must be made with thinner walls than the above.

20. *Tait Gauge. — Volume Increase measured and computed.* — From the dimensions A_0 , A_1 , L , and ρ , given in Table I., it follows that the increase of the external volume of the cylindrical steel tube of the gauge is $47 / 10^6$ per unit of external volume, per centimeter of displacement of the thread of the capillary tube *ss* (Fig. 4). This corresponds to a volume increment

$$v / V = .00000080 \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

per unit of external volume, per atmosphere.

Tait's expression* modified for the present case is

$$v^1 / V = \Pi A_0^2 (1/k + 1/n) / (A_1^2 - A_0^2) \quad . \quad . \quad . \quad (2)$$

where Π is the internal pressure in atmospheres, and k and n the compressibility and the rigidity respectively of the steel employed. Taking k and n from Everett's tables,† viz., $k = 1.84 \times 10^{12}$ and $n = 8.2 \times 10^{11}$, equation (2) becomes, if $\Pi = 10^6$ dynes,

$$v^1 / V = .00000073 \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

This result is of the same order as (1). The difference is in large part due to the constants k and n , which Professor Everett doubtless found for high grade tool steel, whereas the above tubes, being made of a low carbon steel (not temperable), are nearer wrought iron in their properties. Beyond this, the absolute gauge atmosphere is not vouched for; nor are the coefficients at the end of Table I., being mean values between zero and 1,000 atmospheres, free from the thermal discrepancy discussed in § 19.

Similar results might be obtained from Tables II. and III.; but as they are not an essential part of the present paper I omit them.

When observations are made for the purpose of measurement, however, equation (2) may clearly be utilized to obtain serviceable values of $(1/k + 1/n)$. For instance, A_0 may be accurately found by filling the tube with mercury in vacuo, and weighing. From the known density of the steel tube and its weight when empty, A_1 may then be computed. Similarly ρ is capable of accurate measurement. Therefore by combining (1) and (2), $(1/k + 1/n)$ is measurable with the same degree of accuracy with which Π is known.

21. *Digression. Direct Reading (spiral) Bourdon Gauge.* — Endeavoring to achieve this result I multiplied the number of coils, making a helix of five turns as shown in Figure 7. The spires B , C , D , E , F , do not touch one another. The end F is provided with a needle FS , moving over a millimeter scale S , supported by a firm arm TRS . The end A is screwed directly into the barrel. The tube was originally 1 cm. in external diameter and 0.5 cm. in bore. It was flattened parallel to the axis by hammering at red heat, and coiled hot. The internal diameter of the cold helix was somewhat larger than 4 cm., and the upper spire, with its index, extended about a decimeter beyond the helix. The following little table gives the results of a comparissn with the Bourdon gauge.

* Tait, Challenger Reports, Vol. II., 1882, Appendix A, p. 26.

† Everett, Units and Phys. Constants, Macmillan, 1879, p. 53. The data are due to Professor Everett's researches, I believe.

TABLE V.—COMPARISON OF THE SPIRAL GAUGE WITH THE BOURDON GAUGE.

Bourdon.	Spiral.	Bourdon.	Spiral.
atm.	cm.	atm.	cm.
0	0.00	600	1.28
100	0.17	700	1.55
200	0.35	800	1.87
300	0.54	900	2.30
400	0.76	1000	Explosion
500	1.00	0	1.16

Figure 8, which exhibits these data graphically, shows that between zero and 300 atm. the permanent set is not appreciable. When the pressure is taken off, the fiducial zero reappears. Above 300 atm., permanent set becomes very marked. The helix was ruptured at 1,000 atm. Connecting the final zero (after rupture) with the point for 900 atm., a line is obtained more nearly parallel to the line between zero and 300 atm. The mean motion of the index was, therefore, .0017 cm. per atm. Since high pressure measurement is only contemplated, the gauge would have been serviceable except for the occurrence of permanent set. The cause of this insuperable difficulty is the forging necessary to flatten and bend it, for the drawn resilience of the tube is thus destroyed.* Clearly, a cold bent tube might be used without flattening by suitably attaching a mirror index; but this complicates the gauge, and, owing to the great difficulty of working steel, I abandoned further attempts.

22. *Concluding Remarks.*—Instead of having the screw enter the barrel, good results must also be obtainable by forcing a cylindrical shaft into the barrel. The device shown within *CC*, Figure 1, proves that the gasket of marine glue is quite as serviceable for smooth cylinders as for screws. In case of a cylindrical plunger, however, the strain encountered in forcing the plunger home would be brought to bear on the bedplate. Supposing the general disposition to be retained, this would make the apparatus more cumbersome; for specially strong devices would have to be resorted to in bolting down the barrel, etc. Indeed, I mentioned it as an advantage of Andrews's screw, that

* To make the steel Bourdon, it would be necessary to draw flat steel tubes.

the chief stresses exist within the compass of the barrel. I may state, that it was my original object to obviate the necessity of stuffing boxes altogether, by using a *tinned* screw *ST*. The maximum pressure thus obtainable probably exceeds the limit of the above screw compressor. The tinned screw would have a disadvantage in needing to be freshly coated when it became necessary to refill the barrel with oil. Inasmuch, however, as stuffing boxes are thus quite obviated, and as the screw necessary can be cut by very ordinary means in the laboratory, this serviceable device may well be noted.

23. Finally, I observe that, *cæteris paribus*, the labor necessary in producing the above pressures decreases nearly as the fourth power of the diameter of the screw; for friction and leverage both increase as the radius, and the resisting pressure as the square of the radius. Similar advantage is gained by increasing the number of threads to the inch. Hence, by supposing the initial pressures to be produced by a thick screw (diameter one inch, say) at one end of the barrel, and the final pressures (above 2,000 atm., when the enclosed liquids have become much more incompressible) produced by a thinner screw (diameter half an inch, say,) at the other end of the barrel, the practical efficiency of the screw compressor would be increased. In such a case, the piezometer tube must be vertical. § 12. However, in limiting my present work to 2,000 atm., I have by no means exhausted the power of the above machine. My purpose in doing so was to avoid straining the gauges. I add, in concluding, that among the facilities of the above screw compressor is the almost micrometric accuracy with which pressure can be raised to and maintained at a given value for any reasonable length of time.